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SPACE POWER INSULATION INSTITUTE

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SDI-ISTO

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1991 Deptember 15 - 1992 September 14

Space Power Insulation Institute
312 Bonner - ECE - SUNY/AB
Buffalo, NY 14260

Editor
W. J. Sarjeant

1992 August 14

Distribution on last page "(1)"

CONTENTS

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EXECUTIVE SUMMARY

The most practical technological approaches to understanding the behaviour of power conditioning insulation topologies of relevance to SDI have been identified during the first $ 100 k, 12 month phase of this research activity. These are the measurement of microelectrical discharges within and on insulation media through the development of a new generation of partial discharge analysis techniques and systems that reach towards the theoretical noise limit barrier of < 0.1 picocoulombs. Electrochemical aging initiation commences between 0.1 and 0.5 picocoulombs, a level 50 to 200 times LESS than can be measured with commercial systems. The progress this year has been more than projected, with detectivities between 1 and 2 picocoulombs, so that initial insulation aging studies can now commence. For purposes of assessing materials aging under high current faults - both bulk and surface as desired a generalized design 100 kilojoule class 1 to 10 kilovolt reconfigurable capacitor bank has been developed. Passive current limitation has been incorporated with discharge times achieveable from 10 microseconds to milliseconds.

High frequency, high voltage properties of electrical insulation for space applications have been characterized for the first time at high field and voltage levels - to frequencies up to 30 kilohertz and voltages to 5 kilovolts. Degradation has been observed at these high frequences (as will be used in voltage converters or are present in high frequency oscillations observed under insulation fault conditions - such as clearing in metallized capacitors) in the voltage withstand levels, implying significantly reduced life in such systems. This may be minimized for fluid impregnated systems as work this year shows marked reductions an aging rates for such systems wherein the fluid dielectric constants match or exceed those of the insulating materials. The impact of these effects on power densities has been identified as surprisingly significant and aging model development is underway in conjunction with Dr. F. Karasz of the University of Massachusetts, a chemical kinetics specialist.

Several new insulating materials for space applications have been identified and initally characterized. The intent is to be able to replace Kapton films in space systems, particularly wiring, for operation to temperatures above 250 °C. These are the temperatures identified for very compact, high power density space systems of the future, and no materials are yet known to accomplish these missions. At these temperatures, polybenzimidazole films were shown to retain full characteristics to 300 °C, dielectric constants and loss factors not changing also for frequencies up to 100 kilohertz. None of the other materials assessed even remotely approached this level of performance. Thus preliminary work on this material has possibly identified a new insulating material that may well have revolutionary impact on densification of future space systems incorporating electrical power.

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PLANS FOR THE NEXT QUARTER:

As described in the attached letter from George Lee, Dean FEAS, and the memo from Wayne Anderson, Chairman, ECE, FEAS, the space required for the next 12 month phase of this research is being made available over this September-November 1992 time frame. Thus, most of the work efforts this fall will be in actually carrying out the expansion of facilities and rework of the laboratory physical plant to accommodate these new equipments. Completing this will provide high field capabilities up through 1 megavolt impulse, 300 kilovolts AC/DC, and repped to 100 kilovolts, 0.5 through 10 microseconds, at up to 1 kilohertz. Air-testing of large structures will be readily accomplished over these parameter ranges, and plans are underway to extend this into the high vacuum regime through renovation of the very large NASA high voltage, space test vacuum chamber in the new laboratory space. Renovation of the latter will be dominated by resolution of the need for new pumps, and may suggest starting first experiments with the high vacuum system SDI bought for Impulse Engineering, that is now available for the price of refurbishment and shipping.

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June 23, 1992

Dr. Dwight Duston
Director
Innovative Science and Technology
SDIO/TNI
Department of Defense
The Pentagon
Washington, DC 20301-7100

RE: <u>SPACE POWER INSULATION INSTITUTE AT SUNY/BUFFALO</u>

Dear Dwight:

Just a note to let you know that we are progressing on schedule to make space available for Dr. Sarjeant's high voltage experiments, which are scheduled to begin sometime during the fall semester.

We appreciate very much your continued support of the research on space power insulation under the direction of Dr. Sarjeant. I hope that we will continue to achieve excellent results, as we have in the past.

With warmest regards,

Sincerely,

George C. Lee
Professor and Dean

GCL:jg

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July 9, 1992

MEMORANDUM

TO: Prof. W.J. Sarjeant

FROM: Wayne A. Anderson Wayne

RE: Your Request for High Bay Space

We have been able to secure the rear region of high bay in Bonner 126 for your use. This is contingent upon your being funded $300,000 per year for three years. It is my understanding that the project cannot be conducted without this space.

The actual time when the space can be assigned to you is dependent upon a series of moves and renovations. We are proceeding as quickly as possible.

You may call me if there is a need for discussions.

mr

cc R. Dollinger
K. Kiser, Assoc. Dean
G. Lee, Dean
J. Whalen, Assoc. Chair

APPENDIX A

TASK 1.1

IDENTIFY POWER TECHNOLOGY AREAS

Statement of Work - Task 1.1

The Contractor will work on several power conditioning technology areas to determine the most practical technological approaches in insulation materials and topologies that should be explored to enable the government to develop highly compact and reliable SDI power systems. The SPII will continually identify the needed power conditioning areas requiring practical solutions to compact, reliable, high power SDI systems and then match the identified requirements with the existing insulation technology base.

Status

An EMC program to configure a partial discharge analyzer for low level pd signal detection in modulator components is designed and tested. Major areas of electromagnetic interference and non-compatability are identified. Corrective actions implemented in different EMC arenas are discussed. Results of this sub-task were presented at the 1992 IEEE Power Modulator Symposium, Myrtle Beach, SC, June 22-25, 1992. A photocopy of the paper to appear in the symposium proceedings is attached as pages A-3 through A-6.

A 100 kJ capacitor bank with passive fault current limiting was designed. The specifications, such as the impedance of the experimental load and bank capacitor life expectancy (100% = 1,000,000 discharge cycles) can be tailored in the initial design. Detailed results of this work were presented as an ME Project. An Abstract of the ME Project Report is attached as pages A-7 and A-8.

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IDENTIFY POWER TECHNOLOGY AREAS

FACULTY - W. J. Sarjeant
- R. Dollinger

GRADUATE STUDENTS - G. Wolf
- C. Nowak
- J. Stopher

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An EMC Program to Reconfigure a PDA for Low-Level PD Signal Detection in Modulator Components

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Department of Electrical and Computer Engineering
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Buffalo, New York 14260

Richard Dollinger
312 Bonner Hall
Buffalo, New York 14260

Abstract

The electronics industry is rapidly miniaturizing electronic components and systems in an effort to minimize volume, weight, and cost. As a result of these reductions, modulator components must be capable of higher power densities, as well as lower performance degradation due to thermal effects.

In order to make comparative studies of modulator components, a critical issue which needs to be addressed is partial discharge (pd) signal detection in the components under high voltage stress. The Space Power Insulation Institute (SPII) at the State University of New York at Buffalo (SUNYAB) is currently investigating this area using a commercially available Partial Discharge Analyzer (PDA). This PDA is capable of voltage stressing at frequencies of DC, 60 Hz AC, and 60 Hz AC plus DC. The peak voltages are 75 kV DC, 60 kV AC, and 38 kV DC + - 20kV AC.

The PDA's high sensitivity to noise has resulted in implementing a comprehensive grounding, shielding, and noise reduction effort. This paper will present the process used by researchers at SPII to characterize and enhance the detection capabilities of the PDA. It will also describe identification of the major areas of electromagnetic interference and non-compatibility. Finally, the corrective actions that were implemented in different EMC arenas will be discussed.

Although the machine originally measured pd's down to about 200 pC, SPII's challenge was to remove the noise so that the desired pd level for the manufacturer is not only clearly attained, but improved by a factor of 10 to 10 pC.

Figure 1 describes comparative reductions on a test loop and on the system CRT. These pictures illustrate a reduction process which resulted in a factor of 20 improvement overall. The end result will enable researchers at SPII to investigate regimes never before practical with conventional equipment.

This work is partially supported by SDIO-ISTO through the Office of Naval Research grant #N00014-91-J-4114.

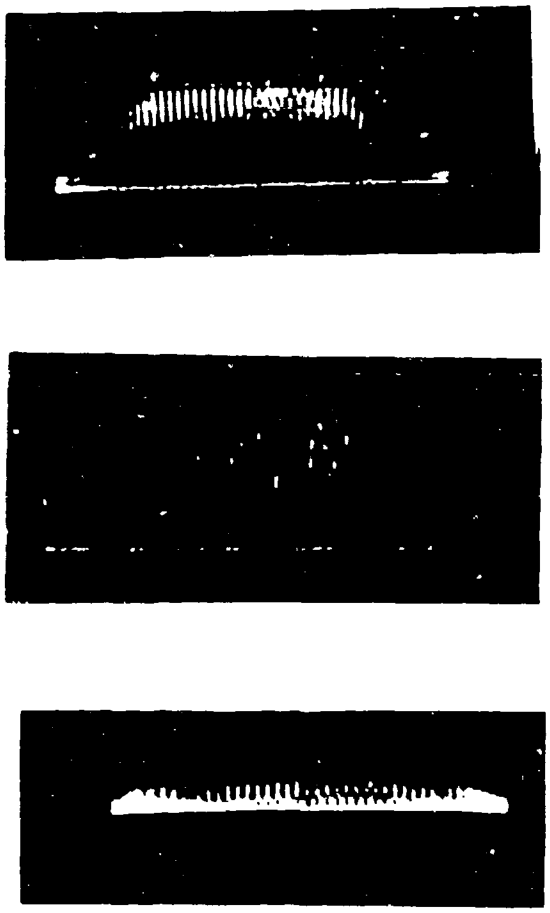

Figure 1. Noise (Arbitrary Scale) displayed on 60 Hz "flattened ellipse" (Gain 100, Vernier at Noon)
Top: Prior to EMC Action, HVAC contactor open
Middle: Same, but contactor closed
Bottom: After EMC Action

I. Introduction

HPE component savings can be realized if the components can be designed to withstand far higher stress levels and high density packaging techniques. This will result in size, weight and cost reductions. Conventional systems to test dielectric withstand voltages and pd's are generally not available to stress insulation at combined AC/DC.

These higher operating stress levels necessitate a more extensive analysis in the role of partial discharges to insulation breakdown. In particular, very low level partial discharges are of interest, so as to see if they have an effect on the ability to predict insulation failure even earlier and avoid the destruction of an expensive component or system.

The PDA is illustrated in Figure 2. It is an overhead view (a spider's eye view from the ceiling) of the electronics bay of the PDA. The large center box is the floor of the PDA, while the outside box is the perimeter of the ceiling and tops of the four walls. The top panel is the front of the PDA if viewed from the inside, and contains controls for AC high voltage and 120/240 VAC power. It also has the signal processing circuitry and system CRT. The left panel holds the safety interlock circuits and has a large opening which goes to the test chamber and power separation filter (PSF). The right panel houses the insertion transformer and some HVDC lines. It also is the main distribution point for most 120 VAC power [illegible] the system [illegible] panel [illegible] the rear of the [illegible], and has the electronics bay access door. It also holds the contactor, some small transformers, and power lines. The floor itself contains the large isolation transformer which brings in all power. It also has the line filter for HVAC, the HVAC transformer, and the variac and stepper controller with stepper motor. The variac is the one which is used to vary the HVAC power for experiments.

II. Procedure

In order to make a comparison in noise reduction, a test loop was placed inside the electronics bay which ran parallel to a significant amount of wire bundles carrying unknown signals. Figure 2 shows the major components in the PDA, and the dashed lines indicate the wire bundles. The solid line is the test loop. Voltage and current measurements were made on the test loop to show a relative degree of inductive and capacitive coupling. These measurements were then used as an indicator of ambient noise.

One fortunate occurrence is that noise appeared on the CRT every time the stepper motor was either staying on or controlling variac voltage. This pointed researchers in a definite direction for EMC improvements. After isolating the general area, a series of

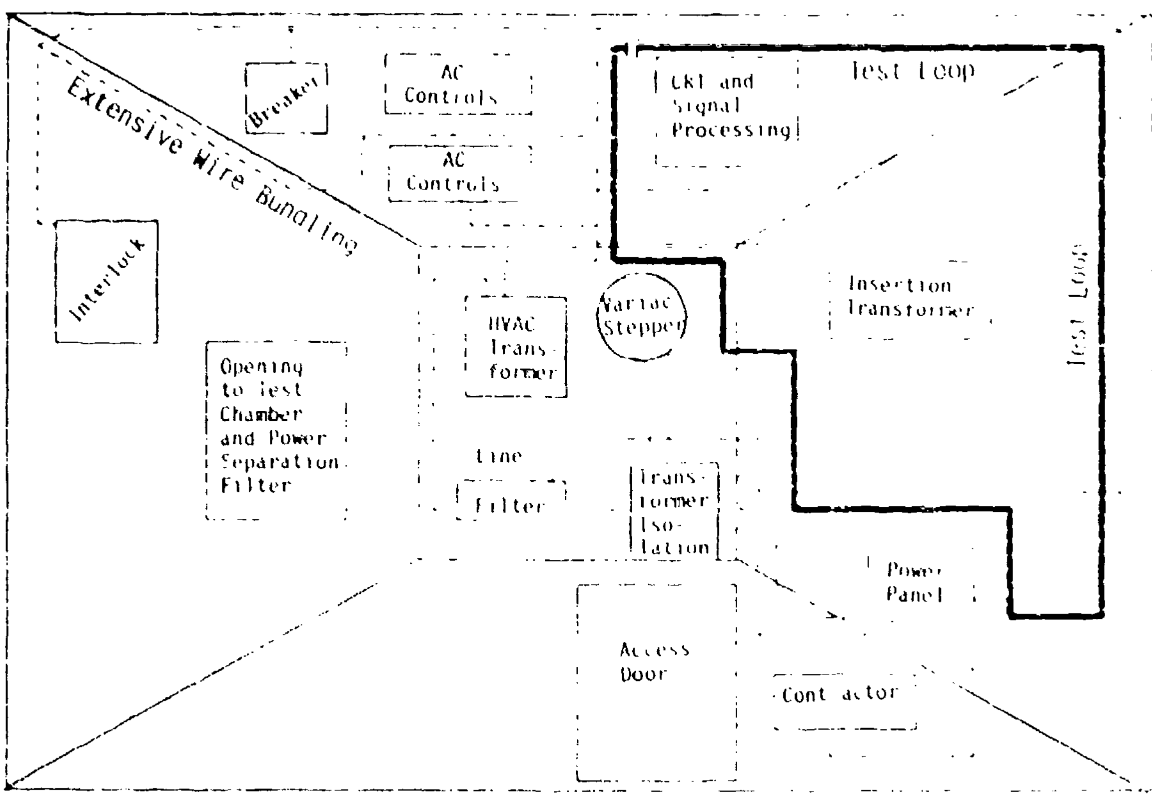

Figure 2. Inside of electronics bay, showing overhead view of PDA

TABLE 1. Noise Abatement Procedure

ACTION	OBSERVATION/RESULTS
IDENTIFICATION	
1. Observe stepper noise on CRT	1. Multi-kilohertz Stronger with contactor closed
2. CRT has been damaged	2. Significant noise challenge
3. Disconnect AC power leads to stepper	3. Noise gone
4. Wire search for coupling noise source	4. Extensive bundling of unlabeled wires in multiple paths makes a wire search difficult
5. Start detailed wire tracing	5. Suspect deleterious loop wiring (instead of separate twisted-wire pairs radiating outward from the isolation transformer)
6. Insert a test loop	6. Open circuit test loop, giving volts to tens-of-volts of noise on loop Short circuit test loop, giving amps to tens-of-amps of noise on loop
7. Wiring harness to be dismantled, reconfigured, and re-wired	7. Attention to Electro-Magnetic Compatibility (EMC) of wiring is necessary In addition, EMC re-wiring now would help to avoid the future existence of other unforeseen noise sources
REDUCTION	
1. Direct AC leads from isolation transformer to stepper	1.
2. All AC power is to be twisted wire pair (greater than 4 turns/inch) with radial feeds to each panel component	2. Removal of deleterious wire loops
3. In particular, a separate wire path is to be run to the stepper motor	3. Reduction of capacitive coupling to other wires
4. Shorter control leads from stepper to front control panel	4.
5. Copper shield box, with coaxial-through-bulkhead pi-filter for AC power, on stepper and motor	5. To reduce capacitive coupling to front panel; (The box is not a solid sealed, RFI enclosure. RFI noise can be addressed later if necessary. If funds and downtime permit, the stepper can be replaced)
6. Coaxial signal cables use a path separate from the other wire bundles	6.
7. Remove AC relay and front panel control switch that is used for shorting out the output of the power separation filter (PSF) at its base; this is used when selecting corona or dielectric testing	7. Replace with manual switch at base of PSF

mitigating actions were performed to reduce interference. The test loop depicted in Figure 2 somewhat paralleled the power lines to the stepper and variac, and was a useful indicator of ambient noise due to these sources.

Table I describes the EMC actions that were taken. It shows the specific actions and the observation/results of those actions. It is divided into two sections; one for the identification stage and one for the reduction stage.

Recommendations

1. Neaten up the interior wiring of the PDA system to ensure EMC.
2. Calibration improvement using accepted international standards & procedures.
3. Aggressive improved safety program for use in a student lab environment.

References

1. "Time Domain Measurements in Electromagnetics", Edmund K. Miller, Van Nostrand Reinhold Electrical/Computer Science and Engineering Series, 1986.

2. "Electromagnetic Compatibility Handbook", J.L. Norman Violette, D.R.J. White, M.F. Violette, Van Nostrand Reinhold Company, New York, 1987.

3. "Biomedical Instruments Theory and Design", Walter Welkowitz and Sid Deutsch, Academic Press, Inc., 1976.

4. "Electromagnetic Compatibility in Radio Engineering", Wilhelm Rotkiewicz, Studies in Electrical and electronic Engineering, Elsevier North-Holland, Inc.,1982.

5. "Principles of Electromagnetic Compatibility", Bernard E. Keiser, Artech House, 1979, ISBN# 0-89006-065-7

6. "Electromagnetic Fields and the Life Environment", Karel Marha, Jan Musil, and Hana Tuha, San Francisco Press, Inc., 1971.

7. "Electrical Interference in Electronic Systems: Its Aviodance within High-Voltage Substations and Elsewhere", R.E. Martin, Research Studies Press, 1979.

8. "Noise Reduction Techniques in Electronic Systems", Henry W. Ott, John Wiley & Sons, 1976.

9. "Grounding and Shielding Techniques in Instrumentation", 2nd Ed., Ralph Morrison, John Wiley & Sons, 1977.

10. "Electrical Safety in Health Care Facilities", Herbert H. Roth, Erwin S. Teltscher, and Irwin M. Kane, Academic Press, 1975.

11. "Electrical Safety Engineering", W. Fordham Cooper, Butterworths Scientific, 1978.

12. "AC Power Handbook- Problems and Solutions", 5th Ed., RTE Deltec Corporation, 1975.

A DESIGN FOR A 100 kJ CAPACITOR BANK
WITH PASSIVE FAULT CURRENT LIMITING

by

Glenn J. Wolf

A Report Submitted to the
Faculty of the Graduate School
of the
State University of New York at Buffalo
in partial fulfillment of the requirements
for the degree of

Master of Engineering

February 1992

A-7

ABSTRACT

A generalized design for a 100. kJ capacitor bank with passive fault current limiting is presented, the goal being that of "tailoring" bank design to the user's specifications. The user will specify crucial operating parameters, namely the impedance of the experimental load and bank capacitor life expectancy (100% life expectancy corresponds to 1,000,000. charge/discharge cycles).

Capacitor fault damage and its effects within the context of nominal bank operation are discussed as a trade-off to the number of modules (1 to 10) and charging voltage (0 to 5 kV). The adaptability of the generalized design is accomplished by not using the old standard method of using a common module bus, but rather the use of separate transmission lines for each module in order to resistively provide a limit to fault current.

APPENDIX B

TASK 1.2

IMPLEMENT INSULATION PROGRAM

Statement of Work - Task 1.2

Implement an R&D program that directly supports ongoing government programs in high energy density components including capacitors, high-power inverters, transmission lines, transformers, and connectors for land and space applications. The new SPII technique for dynamic field grading, that controls the gradient of the electric field in the time domain, is to be applied to both single-shot and high rep-rate insulation topologies relevant to the above systems. Initial studies, executed at 60 Hertz ac, are to be extended into rep-rate pulse assessment in order to increase the voltage stresses applicable to insulating structures for SDI practical applications, such as Laser Radars. The gain in energy density in these topologies is to be determined for a wide range of pulse and rep-rate conditions that are of direct relevance to compact power conditioning systems. Early studies are to be undertaken to advance this laminating technique for dynamics field grading through high stress aging experiments.

Status

High frequency, high voltage properties of electrical insulation and dielectrics for high energy density space power applications, such as those used in capacitors, high power inverters, transmission lines, transformers and connectors are investigated. Properties measured include the breakdown voltage and high voltage aging characteristics at frequencies up to 30 kHz. A noticeable decrease in the dielectric strength was observed with increasing frequency of the applied voltage up to 30 kHz. Also, the life is found to decrease drastically, most probably caused due to heat build-up in the insulation caused by accelerated partial discharge activity and by increased dielectric losses at high frequencies. The results of this work were presented at the 1992 IEEE International Symposium on Electrical Insulation, Baltimore, MD, June 9-11, 1992. A photocopy of the paper presented is attached as pages B-4 through B-7.

The High Energy Density Capacitor Dielectric Mismatch and Aging Characteristics of two dielectric films, PP (Polypropylene) and PVDF (Polyvinylidene Fluoride) with transformer oil and glycerine as the dielectric fluid are investigated using step stress test. Equivalent constant stress lifetimes are estimated for the two configurations from the theoretical model developed. Results show that when the dielectric film is matched with the proper fluid dielectric, an increase in lifetime is observed, Also, the lifetime and breakdown strength ratio is significantly reduced for the dielectric film/fluid mismatch especially in the presence of a void. The results of this work were presented at the IEEE International Power Sources Symposium, Cherry Hill, NJ, June 22-25, 1992. A photocopy of the paper presented is attached as pages B-8 through B-11.

Accelerated life studies of the high temperature dielectric film, Kapton, used for aerospace applications are conducted under multiple stresses. Several theoretical models are applied for the best approach to the experimental data. Analysis of the model parameters show that the present models cannot take into account the acceleration of aging with multiple stresses, and opens up a completely new area of interest to users of electrical insulation for both commercial and military applications for future investigations. The results of this work were presented at the 1992 IEEE International Symposium on Electrical Insulation, Baltimore, MD, June 9-11, 1992. A photocopy of the paper presented is attached as pages B-12 through B-15. Detailed results appear in a Ph.D. dissertation "Accelerated Life Studies of High Temperature Polymide Film Under Simultaneous Electrical and Thermal Multistresses," partially supported by this work, an abstract of which is attached as pages B-16 through B-18.

Additionally, three newly developed high temperature films, PFA (Perfluoroalkoxy), PPX (Poly-P-Xylene) and PBI (Polybenzimidazole) were characterized to explore their possible use as replacement for Kapton in high voltage space wiring applications. The results show that the dielectric properties of PBI film, in particular, remain relatively stable with an increase in temperature of 300 °C. PBI films also exhibits a higher dielectric strength in the higher temperature region (250 °C - 300 °C) as compared to Kapton. The results of this work, also partially supported by NASA, were presented as an invited paper in the Special Session on "Space Power Insulation," at the IEEE International Symposium on Electrical Insulation, Baltimore, MD, June 9-11, 1992. A photocopy of the paper presented is attached as pages B-19 through B-22.

IMPLEMENT INSULATION PROGRAM

FACULTY - W. J. Sarjeant
- J. R. Laghari

GRADUATE STUDENTS - W. Khechen
- P. Cygan
- J. Suthar

Attachments	Page

Conference Record of the 1992 IEEE International Symposium on Electrical Insulation, Baltimore, MD USA, June 7-10, 1992

DIELECTRIC BREAKDOWN OF POLYPROPYLENE UNDER HIGH FREQUENCY FIELDS

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Department of Electrical and Computer Engineering
State University of New York at Buffalo
Buffalo, New York 14260

ABSTRACT

High frequency is widely used in low to medium voltage electronics and power equipment in the aerospace industry in power supplies, inverters, transmitters, radars, etc. With a need for increasing power density, through both voltage and frequency for such applications, there is a need to understand the dielectric behavior of electrical insulation when exposed to high voltage high frequency conditions. Polypropylene, a low loss, high dielectric strength film, is characterized for its dielectric properties under high voltage, high frequency conditions. The properties that are measured include the breakdown voltages and the high voltage aging characteristics at frequencies up to 30kHz. The exponential voltage aging model is used in the analysis of the experimental data, and the constant k and c are calculated for various frequencies. The results of this work are presented in this paper.

INTRODUCTION

Solid insulating materials play a key role in the design and reliable performance of high voltage power equipment as both insulators and charged storage media [1,2]. In future aerospace electronic systems, such as in high power satellites, radars and microwaves, there is need to use much higher voltages and frequencies enabling compactness and light-weight, and to operate under high reliability [3,4]. The high voltage and high frequency conditions will place much greater stress on the power storage and transport components to be used in aerospace power electronic systems. Understanding the failure mechanism of solid dielectrics, especially under long-term exposure to high electric field and high frequency, and developing techniques to predict and improving reliability of these materials, is important for such future aerospace-based systems [4].

In this work, polypropylene film is tested for its dielectric properties under high voltage high frequency conditions. The properties that are measured include the breakdown voltages at frequencies up to 30kHz, and the voltage aging characteristics at selected frequencies. The exponential law is used in the evaluation of the experimental data, and the constants of this voltage aging model are calculated to show their dependency on the frequency of the applied voltage.

EXPERIMENTAL PROCEDURE

The breakdown experiment was conducted in a plexiglass test cell with a fixed bottom electrode and a moveable top electrode. The plane electrodes were made from brass with a diameter of 1.27 cm and rounded edges in accordance with ASTM-D149-81 specifications [5]. All tests were carried out in transformer oil and at room temperature. The test cell was filled with oil so that the sample was covered, avoiding corona discharges around the electrodes edges prior to breakdown. The dielectric material used was a Hercules 8μm thick biaxially-oriented polypropylene film used for high voltage capacitors applications.

Alternating voltage ranging in frequency from 60Hz to 30kHz was used for these experiments. A Powertron 1kVA amplifier with a built-in oscillator Model-1000s was used in series with a 2kVA 5kV transformer to perform the breakdown strength and the voltage aging experiments. The high voltage was connected to the upper electrode through a low-inductance 250kΩ current-limiting resistor to avoid excessive damage to the electrodes, sample and power supply. A 30cm wide copper sheet connected to the upper and lower electrodes served as a low inductance current path. The details of the experimental system are provided elsewhere [6].

Two types of breakdown experiments were performed. First, the breakdown voltage test under a range of frequencies from 60Hz to 30kHz was performed, and at least 9 data points were obtained for each applied frequency. Second, with a predetermined applied voltage stress ranging from 90% to 50% of the breakdown voltage of the specimen, aging experiments were conducted and lifelines were obtained. In this case, the polypropylene film was stressed to the desired voltage, and time was recorded till breakdown occured. The electrodes were cleaned and polished after each set of data points were obtained at each voltage level. The data were computed and then analyzed using the Weibull distribution statistical method [7,8]. The constants of the exponential voltage aging model (k and c) at different frequencies were calculated, and are reported in this paper to show the dependency on the frequency of the applied voltage.

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EXPERIMENTAL RESULTS

The Weibull probability of failure of 8μm polypropylene film as a function of voltage at different frequencies are shown in Figure 1. Only few selected frequencies are shown for the sake of clarity. Figure 2 shows the breakdown voltage (at 63.2% probability) versus applied voltage frequency of the film tested. The data shows that breakdown voltage decreases as the frequency is increased. In particular, there is a steep reduction in the dielectric strength when the frequency is increased from 5kHz to 30kHz. It is well known that partial discharge activity in the microcavities is accelerated with an increase in frequency [9]. This combined with an increased heat loss at the high frequency most probably leads to the reduction in the breakdown voltage.

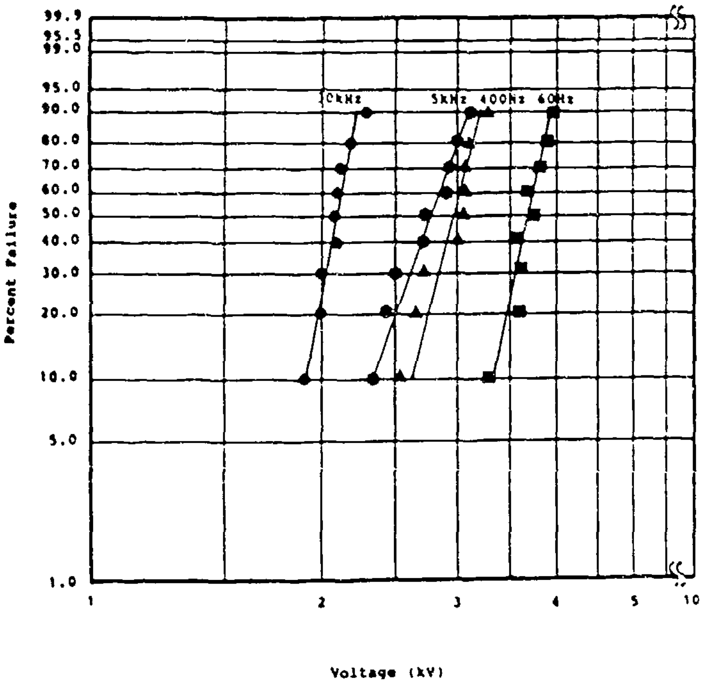

Figure 1. Weibull probability of breakdown of 8μm polypropylene film at various ac frequencies.

The results of the aging studies on the 8μm polypropylene film are shown in Figure 3. The curves represent the Weibull time to break. As was reported previously [6], there is little change in the dielectric constant and dissipation factor of polypropylene for a wide range of frequencies. However, at high electric field stresses at 60 Hz, the dissipation factor increased with an increase in the applied electric field. From the previously observed data of the high field dielectric losses, it also appeared that the partial discharge activity initiated at a voltage around Paschen minimum for air [6,10]. Therefore, in the present set of aging experiments, the reduction in life could most probably be due to film degradation caused by the accelerated partial discharges at high frequenies, as well as heat build-up due to dielectric losses at high voltage, leading to an electrothermal type of breakdown [11,12].

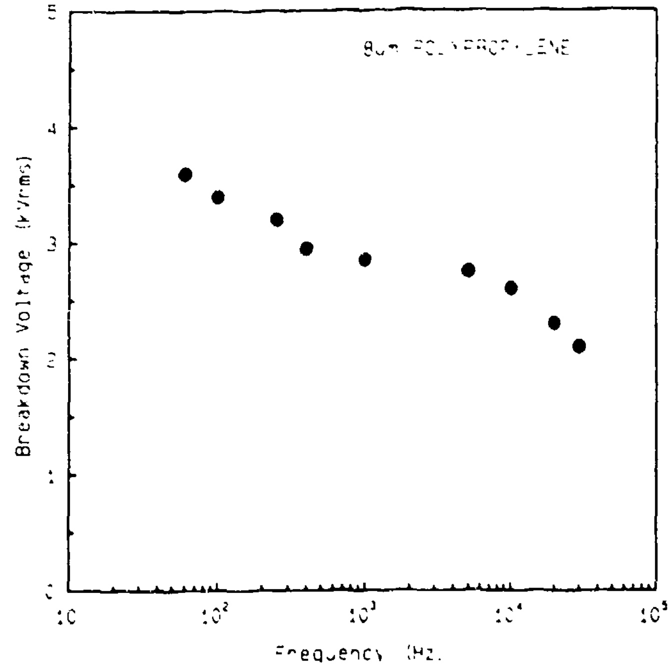

Figure 2. Breakdown voltage of polypropylene film as a function of applied voltage frequency.

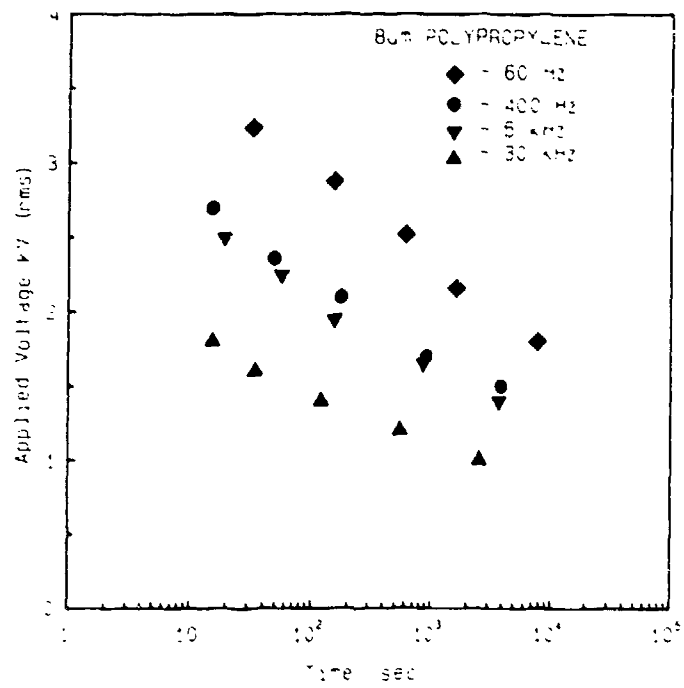

Figure 3. Lifetime of polypropylene film at various ac frequencies.

The exponential voltage aging law , given by

$$t = c \exp(-kV)$$

where t is the time to failure, V is the applied voltage, c and k are constants, was used for the best fit of the experimental data [13]. Table 1 shows the values k and Log c which are also graphed in Figure 4 as a function of frequency. It can be seen that k increases as the frequency is increased. It appears that this constant is somehow related to increased partial discharge activity at high frequency, and therefore, indirectly to the presence of microvoids in the sample [10]. On the other hand, constant c, which decreases with an increase in frequency, may be related to increased dielectric losses at high voltage and high frequency [14]. Additional investigations to understand the dependency of the voltage aging constant on the morphology and other materials properties are currently underway.

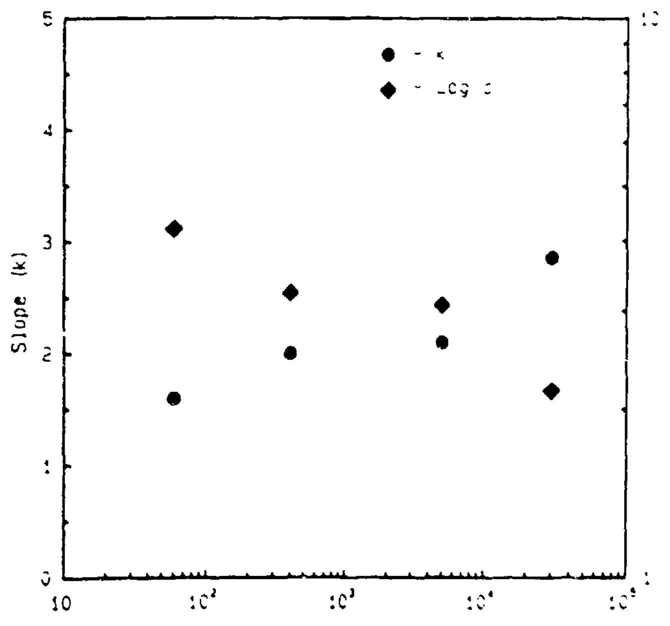

Figure 4. Constants k and c as a function of ac frequency.

Frequency	Slope (k)	Log c
60 Hz	1.6	4.2
400 Hz	2.0	3.2
5 kHz	2.1	3.1
30 kHz	2.9	2.2

Table 1. Values of constants k and c at various ac frequencies.

CONCLUSION

There is a noticeable decrease in the dielectric strength of polypropylene with increasing frequency of the applied voltage up to 30kHz. Also the life is decreased drastically. This decrease is probably due to heat built-up in the insulating film caused by accelerated partial discharges activity and by increased dielectric losses. The constant k of the experimental voltage aging model shows an increase as the frequency is increased. It appears that this constant is somehow related to increased partial discharge activity, and therefore to the presence of microvoids in the dielectric film. However, the constant c decreases with increasing frequency. This may be related to higher dielectric losses at high voltage and high frequency.

ACKNOWLEDGEMENT

This work was mainly supported by NASA Lewis Research Center under Grant No. NAG3-1019, and in part by the Office of Naval Research under Grant No. N00014-19-4114.

REFERENCES

1. W. J. Sarjeant, "Polymer Laminate Structures", Applied Physics Communications, Vol. 3, No. 1&2, pp. 83-167,1983.

2. J. R. Laghari and W. J. Sarjeant, "Energy-Storage Pulsed-Power Capacitor Technology", IEEE Transactions on Power Electronics, Vol. 7, No. 1, pp. 251-257, 1992.

3. National Research Council, Advanced Power Sources for Space Missions, National Academy Press, Washington, D.C. 1989.

4. T. M. Bilodeau, W. G. Dunbar and W. J. Sarjeant, "High-Voltage and Partial Discharge Testing Techniques for Space Power Systems", Vol. 5, No. 2, pp. 12-21, March 1989.

5. ASTM D 149-81, 1987 Annual Book of ASTM Standards, Vol. 10.02, 8 (1986).

6. W. Khachen and J. R. Laghari, "Polypropylene for High Voltage High Frequency Airborne Applications", Conference Record, 1990 IEEE International Symposium on Electrical Insulation, Toronto, Canada, pp. 80-83, June 1990.

7. IEEE Guide for the Statistical Analysis of Electrical Insulation Voltage Endurance Data, ANSI-IEEE STD 930-1987.

8. W. D. Wilkens, "Statistical Methods for the Evaluation of Electrical Insulating Systems", Engineering Dielectrics IIB, ASTM STP # 926, R. Bartnikas (Editor), 1987.

9. T. M. Bilodeau, W. G. Dunbar, and W. J. Sarjeant, " High-Voltage and Partial Discharge TestingTechniques for Space Power Systems", Electrical Insulation Magazine, Vol. 5, No. 2, pp. 12-21, March 1989.

10. W. Khachen, J. R. Laghari and W. J. Sarjeant, "Influence of Space Pressure on Dielectric Properties of Pulsed Power Application", 8th IEEE International Pulsed Power Conference, San Diego, California, pp. 346-350, 1991.

11. Y. Inuishi and T. Suita, "High-Frequency Breakdown of Solid or Liquid Dielectrics", ETJ of Japan, Vol. 1, No. 2, pp. 60-62, 1955.

12. F. S. Ahmed and A. S. Ahmed, "Breakdown of Solid Insulating Film by Partial Discharges Using Sinusoidal and Pulse Voltages", IEEE Transactions on Electrical Insulation, Vol. 13, No. 5, pp. 337-342, 1978.

13. P. Cygan and J. R. Laghari, "A Review of Electrical and Thermal Multistress Aging Models", Conference Record, 1990 IEEE International Symposium on Electrical Insulation, Toronto, Canada, pp. 15-20, June 1990.

14. W. Pfeiffer, "High-Frequency Voltage Stress of Insulation", IEEE Transactions on Electrical Insulation, Vol. 26, No. 2, pp. 239-246, April 1991.

HIGH ENERGY DENSITY CAPACITOR DIELECTRIC MISMATCH AND AGING CHARACTERISTICS

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ABSTRACT

The aging characteristics of two high energy density capacitor dielectric films, polypropylene (PP) and polyvinylidene fluoride (PVDF), with transformer oil and glycerine as dielectric fluids, were obtained using step-stress test. The inverse power law was used in the analysis of the experimental data. With the value of power exponent determined from the step-stress for each dielectric film/fluid combination, an equivalent constant stress lifetime were estimated for the two configurations tested (with and without a void in the middle layer). The results show that lifetime is longer for the matching dielectric film /fluid combination. Also, the lifetime and the breakdown strength ratio is significantly reduced for the dielectric film/fluid mismatch especially in the presence of a void.

INTRODUCTION

A capacitor is the primary energy storage device for high energy applications [1]. Capacitors are also widely used for high voltage pulsed testing of power transformers, cables and apparatus. The commonly used dielectric materials in high energy density capacitors, such as polypropylene (PP) and polyvinylidine fluoride (PVDF), are always associated with imperfections, voids and microcavities during the manufacturing process. To improve the electrical quality reliability of these dielectric films and make them partial discharge free in the presence of applied high voltage, a good matching dielectric fluid is generally recommended to be used with the dielectric film.

Accelerated aging tests, such as increasing frequency, temperature, voltage, etc. are widely accepted in the testing of dielectric materials used in cables, capacitors and other applications [2,3]. The step-stress test is another method which has been used in evaluating the equivalent constant stress life of dielectric films [4,5]. Recently, it has been successfully used to estimate the constant stress lifetime of polypropylene fiim [6].

The step-stress model is based on the inverse power model, which has been frequently used to estimate lifetimes of insulating materials under constant voltage stress [2]. In the simplest form, this model is represented by the equation

$$tV^n = k \qquad (1)$$

where t is the time to breakdown at voltage stress V, n and k are constants. Assuming a cumulative nature of the damage to the insulation, the inverse power model can also be applied to step- stress test [5]. In this procedure, the voltage is raised in steps and held constant at each step for some time interval. The cumulative damage is then simply the sum of damages at each voltage level. This relation is represented by

$$t_k(V_k)^n = \Sigma t_i(V_i)^n + t_{i+1}(V_{i+1})^n \qquad (2)$$

where t_k is equivalent time to failure at voltage stress V_k, t_iV_i is a product of voltage and time at each fully completed step, and t_{i+1} is the time of failure on the uncompleted V_{i+1} step. Setting the step intervals t_i in the experiment to be equal, this equation can be greatly simplified and is easier to analyze. Furthermore, this implies that the right side of equation (2) can be treated as a constant and independent of the time interval t_i, provided the aging mechanism has not change over the covered range. Using this assumption, the exponent of the power model can be easily determined by performing several tests with different time intervals t_i, and then used to estimate the lifetimes under constant stress.

In this work, the lifetime of two different high energy density capacitor dielectrics, PP and PVDF, with transformer oil and glycerine as the dielectric fluid, were estimated using step-stress test. Two configurations of three layers of the dielectric film, with and without an artificial void in the middle layer, were used for each dielectric film/fluid combination to determine the degree of matching of the dielectric film and the dielectric fluid on the aging characteristics. The experimental procedure and experimental results are described below.

EXPERIMENTAL PROCEDURE

Two configurations of the dielectric films, PP and PVDF, that were estimated for lifetime. The first configuration consisted of three layers of the dielectric materials (8 µm, 8 µm and 8 µm of PP; 12.5 µm, 12.5 µm and 12.5 µm of PVDF). In the second configuration, an artificial void was introduced in the middle layer by piercing a needle (25 µm in diameter) through the film. The relative dielectric constants of PP and PVDF were measured to be 2.2 and 10.6 respectively.

Standard cylindrical stainless steel electrodes 2.54 cm in diameter with rounded edges in accordance with ASTM-D149-81 specifications were used. The tests were carried out in transformer oil and glycerine having dielectric constants of 2.3 and 42, respectively, at room temperature [7]. An ac dielectric test set (Hipotronics Model 7100-20) was used as the power supply. It had an overcurrent protection which enabled the high voltage to turn off automatically whenever breakdown occurred. The high voltage terminal was connected to the upper electrode through a 250 kΩ current limiting resistor.

In these experiments, three different time intervals t_i for the step-stress method were selected (20, 45 and 120 sec). These steps were selected based on its success in estimating the lifetime of PP film in an earlier experiment [6]. The voltage was raised in steps of 500 V and held constant until breakdown occurred. The total time of applied stress and the voltage at which the sample failed were recorded. Nine data points were obtained for each time interval and for each configuration. Weibull distribution was used to calculate the scale α parameter.

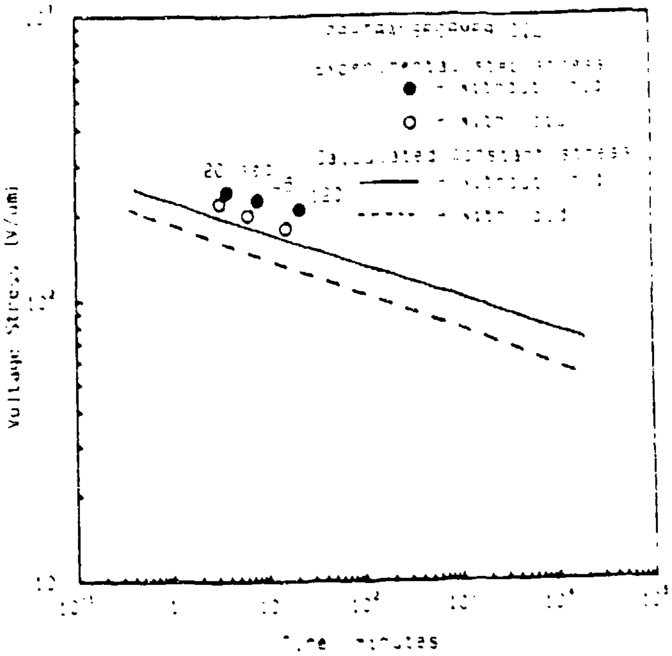

Figure 1. Voltage stress versus life of PP and transformer oil under experimental step-stress and calculated constant stress.

EXPERIMENTAL RESULTS

The results of the step-stress test for the polypropylene in transformer oil and glycerine are shown in Figures 1 and 2 respectively; while that for polyvinylidene fluoride in transformer oil and glycerine are shown in Figures 3 and 4, respectively. The times represent the scale parameter α of the weibull distribution from the data collected. The three data points of the step-stress test, as shown in the figures, represent the time failure for the first configuration (without the void) for intervals of 20, 45 and 120 seconds. A linear fit was used to obtain the best fitting line for the dielectric materials tested in both transformer oil and glycerine (Figures 1 through 4). The slope of the lines were then used to obtain the power exponents (n), which are shown in Table 1. In addition, for each interval, the right side of equation 2 was calculated. The values of the constants for each dielectric film (PP and PVDF with transformer oil and glycerine) for both configurations (with and without an artificial void in the middle layer) are also shown in Table 1.

The calculated constant stress lifetimes (for 20 seconds time interval values) for PP and PVDF with transformer oil and glycerine as dielectric fluids for both configurations (with and without a void in the middle layer) are plotted as a solid line in Figures 1, 2, 3 and 4, respectively. (The results calculated for the 45 and 120 seconds showed close proximity to 20 seconds results and are, therefore, not shown in the figures for clarity purpose). It can be seen from these results that there is a significant decrease in the calculated constant stress life in the presence of the void especially for the dielectric film/fluid mismatch, such as PP/ glycerine (Figure 2), and PVDF/transformer oil (Figure 3). For the case of matching film/fluid, the reduction in life in the presence of void is less than in the previous cases (Figures 1 and 4).

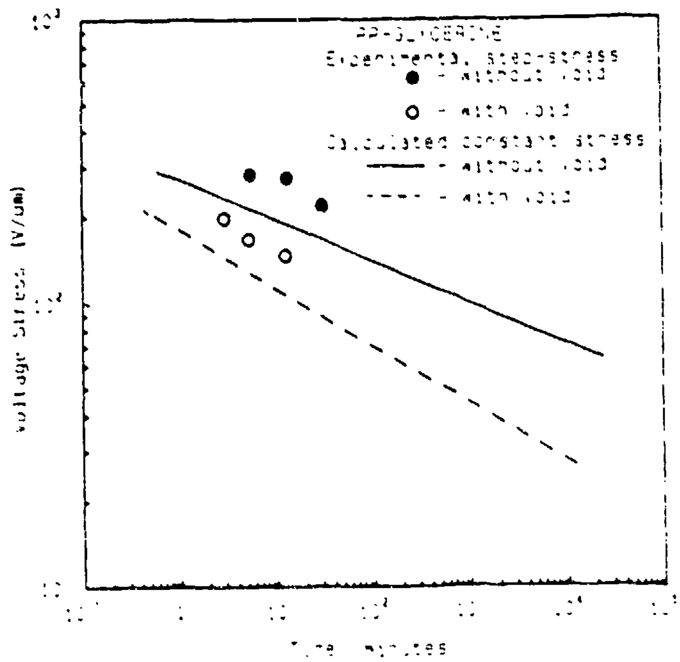

Figure 2. Voltage stress versus life of PP and glycerine under experimental step-stress and calculated constant stress.

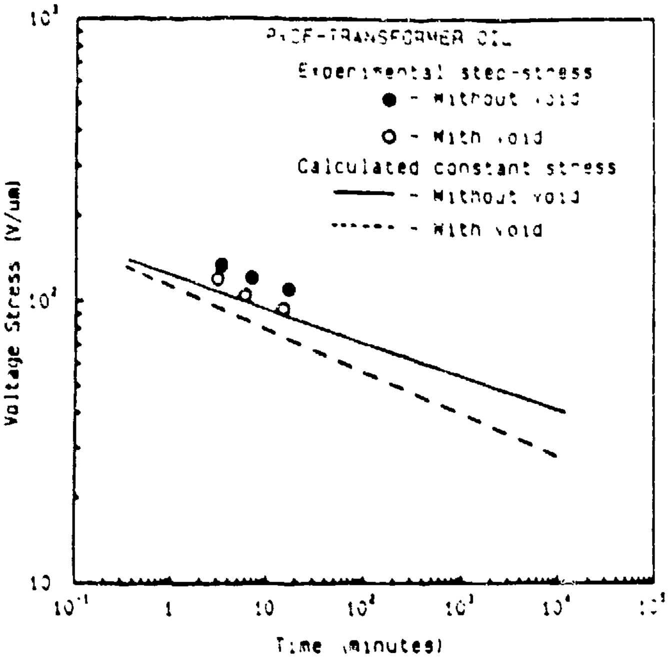

Figure 3. Voltage stress versus life of PVDF and transformer oil under experimental step-stress and calculated constant stress.

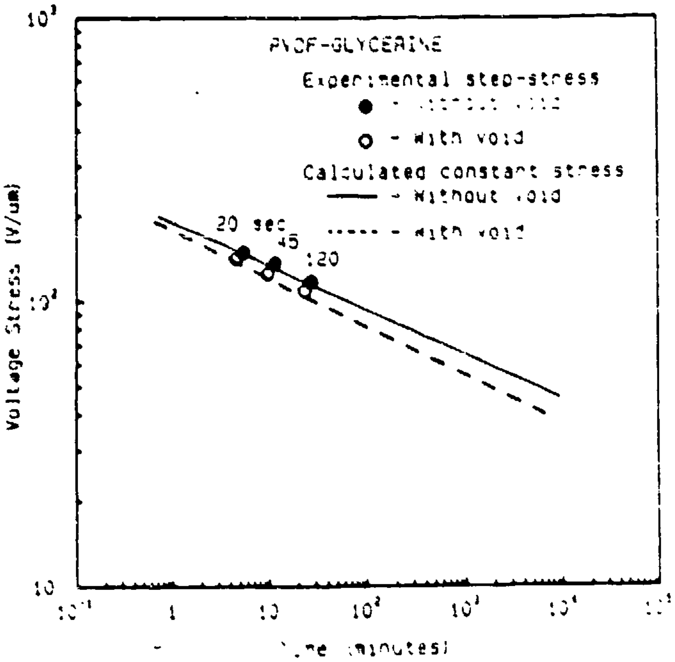

Figure 4. Voltage stress versus life of PVDF and glycerine under experimental step-stress and calculated constant stress.

		Without void		With void	
		n	K (t = 20 sec)	n	K (t = 20 sec)
PP	T-oil	8 5	1 7 x 10^6	7 8	[illegible]
	Gly	6 8	3 8 x 10^5	4 9	[illegible]
PVDF	T-oil	8 3	1 2 x 10^4	6 6	[illegible]
	Gly	6 4	2 7 x 10^3	5 9	[illegible]

Table 1. Values of constants n and K (equation 2) for PP and PVDF in T-oil and glycerine.

Table 2 shows the ratio of the breakdown voltages of PP and PVDF with and without a void in the middle layer in transformer oil and glycerine. It can be seen that PVDF/transformer oil and especially PP/glycerine show lower breakdown voltage ratios, while matching the dielectric film to the fluid (PP/transformer oil and PVDF/glycerine) significantly improves the breakdown strength ratio. This behavior is probably due to the fact that the fluid dielectric which matches the dielectric constant of the film causes a uniform electric field distribution across the void surface and therefore a higher breakdown voltage [8].

	T-oil	Glycerine
PP	0.95	0.7
PVDF	0.89	0.93

Table 2. Ratio of breakdown voltages of PP and PVDF with and without a void in T-oil and glycerine.

Figure 5 summarizes the constant stress aging characteristics calculated for the various configurations. It can be seen that at lower field stress, the aging characteristics tend to interchange. These could be due to a different failure mechanism not operative at higher field stresses and, therefore, are not covered by the present set of experiments.

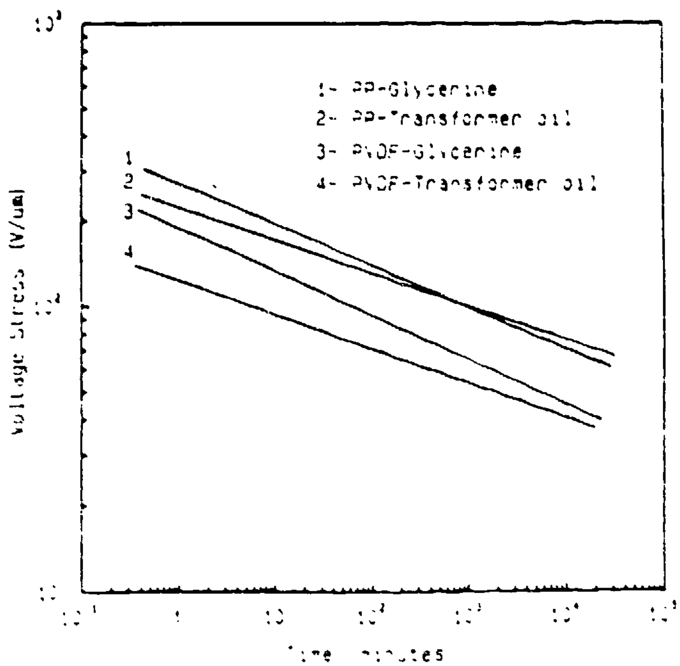

Figure 5. Calculated constant stress life of PP and PVDF in transformer oil and glycerine.

CONCLUSION

The constant stress lifetimes of two dielectrics films, PP and PVDF, with transformer oil and glycerine as the dielectric fluid are calculated from the step-stress test. Results show that when the dielectric film is matched with the proper fluid dielectric, an increase in lifetime is observed. Also, the lifetime and the breakdown strength ratio is significantly reduced for the dielectric film/fluid mismatch especially in the presence of a void.

ACKNOWLEDGEMENT

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REFERENCES

1. J. R. Laghari and W. J. Sarjeant, "Energy-Storage Pulsed-Power Capacitor Technology", IEEE Transactions on Power Electronics, Vol. 7, No. 1, pp. 251-257, 1992.

2. P. Cygan and J. R. Laghari, " Models for Insulation Aging Under Electrical and Thermal Multistress", IEEE Transactions on Electrical Insulation, Vol. 25, pp. 923-934, 1990.

3. D. R. Johnston, J. T. LaForte, P. E. Podhorez and H. N. Galpern, "Frequency Acceleration of Voltage Endurance", IEEE Transaction on Electrical Insulation, Vol. EI-14, pp. 121-126, 1979.

4. S. E. Kiersztyn, " Formal Theoretical Foundation of Electrical Aging of Dielectric", IEEE Trans. Pow. App. Sys., Vol. 100, pp. 4333-4340, 1981.

5. W. T. Starr and H. S. Endicott, " Progressive Stress- A New Accelerated Approach to Voltage Endurance, AIEE Trans. Pow. App. Sys., Vol. 80, pp. 515-523, 1961.

6. J. R. Laghari, P. Cygan and W. Khachen, " A Short Method of Estimating Lifetime of Polypropylene Film Using Step-Stress Tests", IEEE Transaction on Electrical Insulation, Vol. 25, pp. 1180-1182, 1990.

7. Handbook of Chemistry and Physics 62nd Edition, pp. E-53, 1981-1982.

8. J. R. Laghari, A. N. Hammoud and W. J. Sarjeant, "Time-Induced Partial Discharge Breakdown in Laminate Structures", IEEE Conference on Electrical Insulation and Dielectric Phenomena, Amherst, New York, pp. 518-523, 1985.

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ACCELERATED LIFE STUDIES OF POLYIMIDE FILM UNDER ELECTRICAL AND THERMAL MULTISTRESS

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ABSTRACT

Accelerated life studies on a high temperature polyimide film (Kapton®) were conducted under simultaneous electrical and thermal multistress at 60 Hz and 400 Hz. The breakdown strength and the aging characteristics were obtained at test temperatures of 23° C, 100° C and 200° C. Two parameter Weibull distribution was used in the evaluation of the experimental data. The experimental results show that electrical aging, both by increasing the applied voltage or the applied frequency, is the responsible failure mechanism under these conditions, and that thermal aging is not a major degradation factor for the Kapton film in the applied temperature range particularly at the higher frequency of 400 Hz. Several theoretical models were applied for the best approximation to the experimental data. Analysis shows that the present physical models can not take into account accelerated aging with the applied frequency.

INTRODUCTION

One of the most critical aspect of the design and applicability of any equipment is its reliability and life. With advances in high voltage aerospace and military technology, there is a greater need for components to operate under higher frequencies, electric fields and temperatures. A large number of these components operate at 400 Hz, and in some cases, at temperatures as high as 200° C.[1] Due to these high operating temperatures, Kapton® polyimide is the commonly used electrical insulation for such applications.

It is well known that failure in most high voltage components is largely attributable to the degradation and aging of electrical insulation under multifactor stress aging.[2] The aging process can be significantly accelerated at higher frequencies, electric fields and temperatures, thereby leading to a much reduced life and premature failure. No data on the high frequency high temperature aging of electrical insulation is currently available in the literature.

In the work, accelerated life studies of Kapton® polyimide film were conducted under electrical and thermal multistress. Several theoretical models were applied for the best approximation to the experimental data, and the results are analyzed to understand what effect, if any, the applied frequency has on the model parameters.

EXPERIMENTAL PROCEDURE

Kapton® polyimide type HN (100 HN) film of thickness 25.0 μm was used in the lifetime studies. It is an all purpose film which can used in a wide temperature range (-269° C to 400° C), and can be laminated, metallized, or adhesive-coated. The properties of the film are listed in reference.[3,4] Dow Corning 210 H Silicon fluid was used in conjunction with the dielectric film. It is a dimethyl polysiloxane fluid which is characterized by high oxidation stability, outstanding resistance to high temperatures, gelation and weight loss.[5] These are the types of properties required by the nature of the long-term (at elevated temperatures) aging experiments.

Standard cylindrical brass electrodes, 2.54 cm in diameter with rounded edges in accordance with ASTM-D149-81 specifications, were used for the aging experiments. A fixture made of high temperature resistant and machinable ceramic material, Macor glass, manufactured by Corning, was used to support the electrodes. The electrode assembly with the sample was submerged in the silicone oil in a metal container. This also allowed the whole set-up to be heated uniformly to the required temperature by means of a hot plate heater, with the temperature rate controlled by the voltage regulator of the heater. A temperature sensor, connected to the digital thermometer, also allowed constant monitoring of the temperature close to the sample. The upper electrode was connected to the high voltage supply through a 250 kΩ current limiting resistor. A Hipotronics ac 60 Hz and a Powertronics high frequency 400 Hz power supply was interchangably used for these experiments. The voltage was raised at a rate of 500 V/sec to the required level (some percentage of the breakdown voltage at room temperature) for the constant stress aging experiments. A Tektronix P6015 high voltage probe was used to monitor the voltage on an oscilloscope.

All 60 Hz and 400 Hz tests were performed at three temperatures: 23°, 100°, and 200° C. After a waiting period

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of two minutes to bring the temperature of the sample to the required level, the voltage was applied. On an average, about nine points were taken for each measurement condition.

EXPERIMENTAL RESULTS

Since failure data is statistical in nature, various distributions are normally used. For lifetime data of solid films, the Weibull distribution

$$F(x) = 1 - \exp\left(-\frac{x}{\alpha}\right)^{\beta} \qquad \text{...(1)}$$

with scale parameter (α) and shape parameter (β), has been found to be the most suitable.[6] The scale parameter is reported as the time-to-failure (or voltage).

The life curves of the polyimide film for 60 Hz and 400 Hz at temperatures of 23°, 100° and 200° C are reported in Figures 1 and 2, respectively. Each data point on the curve represents a 63.2% failure probability at the applied voltage, which is 90%, 80, 70, 60, 50 or 40% of the breakdown voltage measured at 23° C. The results show that the aging process is clearly accelerated by increasing either the applied voltage or the applied frequency from 60 Hz to 400 Hz. Though increasing the temperature accelerates the aging process at 60 Hz (Figure 1), it appears from the experimental results that aging is not accelerated due to just an increase in the temperature alone, i.e. from 23° C to 200° C, at 400 Hz (Figure 2).

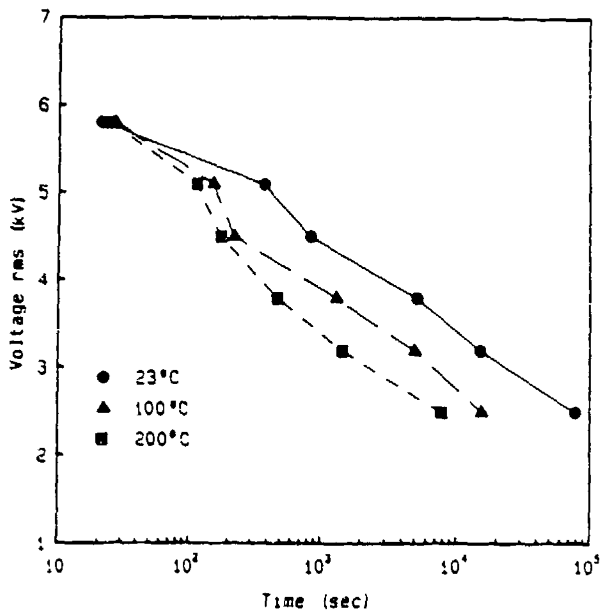

FIGURE 1: *Lifetimes of Polyimide film 100 HN Kapton at 60 Hz (Film Thickness 25.0 μm).*

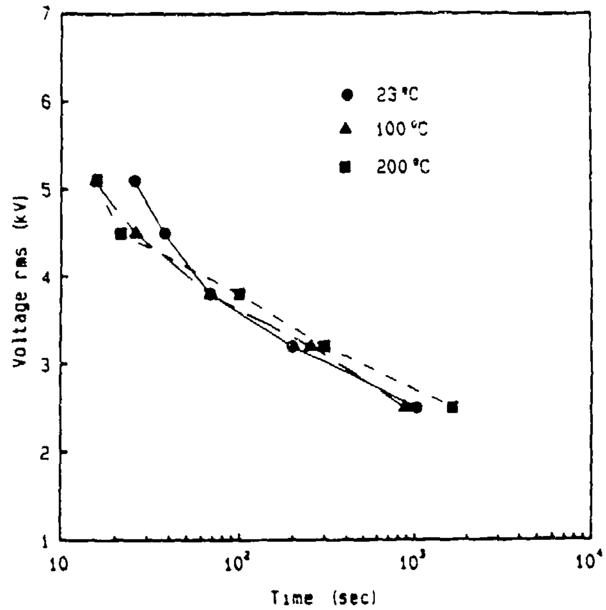

FIGURE 2: *Lifetimes of Polyimide Film 100 HN Kapton at 400 Hz (Film Thickness 25.0 μm).*

MULTISTRESS AGING MODELS

Inverse power and exponential relations have been frequently used to estimate life of insulating materials under constant voltage stress. In its most basic form, these models are represented by

$$t V^{n} = K \qquad \text{...(2)}$$

and

$$t = C \exp(-KV) \qquad \text{...(3)}$$

where t is the time to breakdown (or life) at voltage stress V, and n, K, and C are constants to be determined[2]. To test the validity of these models, the data is plotted on a log-log scale for the power model, and semi-log scale for the exponential model to see if a straight line results.

A modification of the power model, as applied to the combined electrical and thermal multistress, is given by [7-9]

$$\log t = (\log K - B\,\Delta T) - (n_1 - n_2\,\Delta T)\log E \qquad \text{...(4)}$$

where n1, n2, K and B are constants determined experimentally, and $\Delta T = [1/T_0] - [1/T]$ (T_0 is the room temperature and T is the absolute temperature). Similarly, a modification of the exponential model, as applied to combined electrical and thermal multistress, can be given by [8,10]

$$\log t = \left(\log A_1 + \frac{B_1}{T}\right) + \left(A_2 + \frac{B_2}{T}\right) E \qquad \text{...(5)}$$

where A1, A2, B1 and B2 are constants determined experimentally.

The calculated parameters of the multistress power model (Equation 4) and the exponential model (equation 5) for the experimentally tested 60 Hz and 400 Hz are given in Tables 1 and 2, respectively. The model parameters clearly show a dependency on the applied frequency.

Test	n_1	n_2	log K	B
60 Hz	7.69	1.26E+03	8.00	6.04E+02
400 Hz	5.14	1.23E+03	4.93	3.08E+02

Table 1: Calculated Parameters of the Multistress Power Model .

Test	A_1	A_2	B_1	B_2
60 Hz	6.45	-0.88	2.95E+03	-3.65E+02
400 Hz	14.47	-2.56	-1.36E+03	3.49E+02

Table 2: Calculated Parameters of the Multistress Exponential Model .

Another model developed recently, and often dubbed as the physical model, is given at high electric field, by [11]

$$t = \left(\frac{h}{kT}\right) \exp\left[\frac{(\Delta G - e\lambda E)}{kT}\right] \qquad ...(6)$$

where h and k are the Plank and Boltzmann constant, respectively, and ΔG and λ are some form of energy and barrier width. The dependence of this models' parameters, ΔG and λ, on both temperature and frequency, are shown in Figures 3 and 4, respectively. A distinct feature of this model is the strong dependence of its parameters with increasing temperature. A completely new observation in the present set of experiments is the reduction of both parameters (Δ G and λ) with an increase in frequency of the applied electrical stress, especially at the two lower temperatures, as can be visualized in Figure 3 and 4, respectively. The reasons of frequency dependence of the constants of the physical model are not clear at this point, and additional experiments are currently underway.

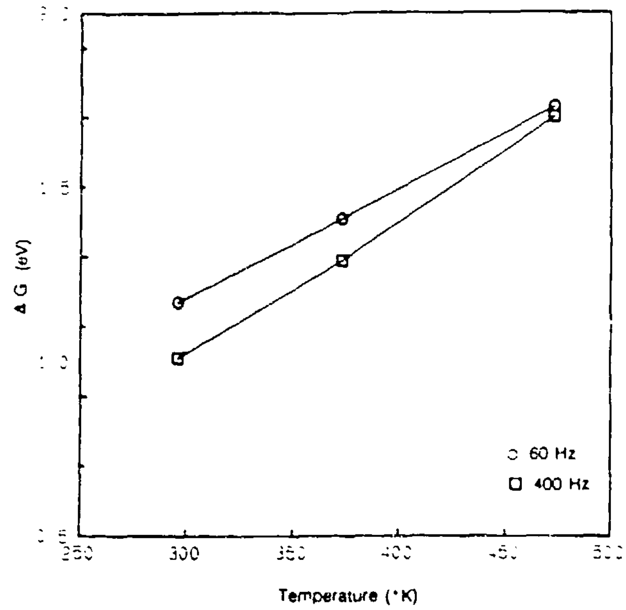

FIGURE 3: Dependence of ΔG on Applied Temperature for 100 HN Kapton Film.

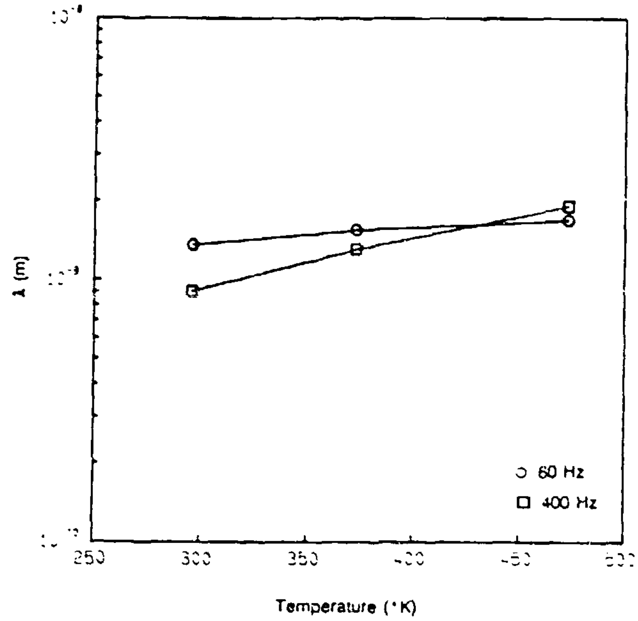

FIGURE 4: λ as a Function of Applied Temperature for 100 HN Kapton Film.

CONCLUSION

The power and the exponential models, being basically empirical formulae, have no physical meaning other than defining the degradation rate as power or exponential dependent. Even through the physical model offers such an explanation, the experimental data and the model parameters indicate inconsistency with the accelerated frequency data. Analysis of the model parameters show that the present models can not take into account the acceleration of aging with applied frequency, and opens up a new area of interest to users of electrical insulation for both commercial and military applications for further investigation.

ACKNOWLEDGEMENTS

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REFERENCES

[1] J. Van Leak, "Kapton Wire Concerns for Aerospace Vehicles", Workshop on Wiring for Space Applications, NASA LeRC, Cleveland, Ohio, July 1991.

[2] P. Cyan and J. R. Laghari, "Models for Insulation Aging under Electric and Thermal Multistress", IEEE Transactions on Electrical Insulation, Vol 25, pp 923-934, 1990.

[3] W. T. Shungg, *Handbook of Electrical and Electronic Insulating Materials*, Van Nostrand Reinhold, NY, 1986.

[4] Du Pont, *Kapton - Polyimide Film : Summary of Properties*, Bulletin !o 72087, 1986.

[5] Dow Corning, Information about Silicone Fluids: 210H, 1980.

[6] IEEE Guide for the Statistical Analysis of Electrical Insulation Voltage Endurance Data, ANSI / IEEE Std 1930-1987.

[7] L. Simoni, "General Equation of the Decline in Electric Strength for Combined Thermal and Electrical Stress", IEEE Transactions on Electrical Insulation, Vol 19, pp 45-52, 1984.

[8] B. Hemalatha and T. S. Ramu, " Insulation Degradation under Multifactor Stress", 5th Int. Symposium on High Voltage Engineering, Braunshweig, Germany, August 1987.

[9] S. M. Gubanski, "Analysis of Life Time Estimation Methods Based on Data for Electro-Thermally Aged PET Films", IEEE Int Symposium on Electrical Insulation, Toronto, Canada, pp 27-30, June 1990.

[10] B. Fallou, C. Burguiere and J. F. Morel, "First Approach on Multiple Stress Accelerated Life Testing of Electrical Insulation, Proceedings CEIDP, Pocono PA, pp 621-628, 1979.

[11] J.-P Crine, J.-L Parpal and Ch. Dang "A New Approach to the Electrical Aging of Dielectrics", Proceedings CEIDP, Leesburg, VA, pp 161-167, 1989.

ACCELERATED LIFE STUDIES OF HIGH TEMPERATURE POLYIMIDE FILM

UNDER

SIMULTANEOUS ELECTRICAL AND THERMAL MULTISTRESSES

by

Peter J. Cygan

A dissertation submitted to
the Faculty of Graduate School of
State University of New York at Buffalo
in partial fulfillment of the requirement for the degree of
Doctor of Philosophy

February 1992

ABSTRACT

Accelerated life tests on a high temperature polyimide film (Kapton®) were performed under simultaneous electrical and thermal stresses. Samples of 25 μm thick films were immersed in the silicon oil and stressed electrically between two cylindrical electrodes. The oil was heated to test temperatures of 23°C, 100°C and 200°C. At each temperature, the breakdown strength and lifetime tests were performed at 60 Hz and 400 Hz. In addition, a progressive (step-stress) test was performed at room temperature and a frequency of 60 Hz. The two parameter Weibull distribution was used in the evaluation of the experimental data. For each set of the data, the scale and shape parameters, and 90% confidence intervals were calculated using a computer routine based on the maximum likelihood function. The results from 60 Hz, 400 Hz and step-stress tests were compared, and several theoretical models were applied for the best approximation to the experimental data.

It was found that accelerated life tests are possible through conducting the test at increased frequency or by using the progressive test and simultaneous application of increased temperature. In a relatively short time, very good results (conforming to the linear relationship describing reduced life span for the dielectric) are achieved with increasing the frequency of applied voltage to 400 Hz. On the other hand,

the application of the step-stress method generates complete data sets in a far shorter time frame with equally valid results. Since both methods - increased frequency and step-stress - produce the acceleration of only electrical aging, very small changes are observed for the thermal aging alone. In fact, Kapton® film proves to be very stable in the applied range of temperatures. It is concluded that the electrical aging, both by increasing the applied voltage or the applied frequency, is responsible for the failure mechanism under these conditions and that thermal aging is not a major degrading factor in the life of Kapton® film in the applied temperature range.

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EVALUATION OF DIELECTRIC FILMS FOR AEROSPACE AND SPACE POWER WIRING INSULATION

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ABSTRACT

Three high performance dielectric films, Perfluoroalkoxy (PFA), Poly-P-Xylene (PPX), and Polybenzimidazole (PBI), were characterized to explore their possible use as a replacement for Kapton® in high voltage wiring insulation. The dielectric properties of PFA and PPX, including permittivity and dissipation factor, were obtained in a frequency range of 50 Hz to 100 kHz and at temperatures up to 200° C, and the ac dielectric strength was determined at temperatures up to 250° C. For PBI, the dielectric properties were obtained at temperatures up to 250° C and the dielectric strength at temperatures up to 300° C. The experimental results are compared with those of Kapton. The results obtained indicate that PBI film can successfully withstand higher temperatures up to 300° C and maintain all its electrical properties at elevated temperatures. On the other hand, PFA and PPX dielectric films, like Kapton, are capable of maintaining their electrical properties, with minimal degradation, at temperatures up to 200° C. PFA, PPX and PBI are thus promising candidates for high voltage aerospace and space power applications, in particular at high temperatures.

INTRODUCTION

Polyimide (Kapton®) is widely used for wiring insulation - MIL W81381 (cable) and energy storage (capacitor) and in aerospace and space power systems. However, key problems associated with the use of Kapton are arc-tracking and cracking under a combination of high temperature and humidity. [1,2] Kapton-insulated systems are thus susceptible to fire hazard due to intense and repeated arc-tracking.[3] Such failure modes in Kapton have been identified mostly due to loss of electrical and mechanical properties. A recent report shows that MIL W81381 cables have failed prematurely in a number of a air force, naval and space power applications.[4] Therefore, there is a need to identify alternate high performance insulating material which can maintain physical integrity and dielectric properties, as well as offer reliability over the wide range of temperature conditions.

Three high temperature films, Teflon® Perfluoroalkoxy (PFA), Poly-P-Xylene (PPX), and Polybenzimidazole (PBI), were selected for further high temperature high voltage evaluation after a detailed literature search. PFA is similar to Teflon PTFE but has superior electrical and mechanical properties.[5] PPX is used for some microelectronic low voltage earth-based applications, such as for coating printed circuit boards and barrier protection.[6] PBI has been mainly used as a thermal blanket for missile applications,[7] but has not yet been employed for high voltage cable insulation. Some key properties of these insulating materials along with Kapton are listed in Table 1. [5,6,8,9] Very little information is, however, available on their high voltage characterization at high temperatures.

	Kapton	PFA	PPX	PBI
Melting Point (°C)	370	310	420	> 600
Max. Service Temperature (°C)	260	260	260	315 - 370
Dielectric Constant	3.0 - 3.4	2.0	2.65	4.4 - 16.2
Dissipation Factor	0.0025	0.0002	0.002	0.024 - 0.57
Dielectric Strength (V/μm)	275	157 - 196	275	157 - 275
(kV/mil)	(7)	(4 - 5)	(7)	(4 - 7)
Tensile Strength ($\times 10^7$ N/m^2)	17.2	2.7 - 4.8	4.68	11.7 - 18.6
Density (g/cc)	1.42	2.2	1.2	1.2

TABLE 1 Key Properties of Selected High Temperature Insulating Materials as Reported in the Literature.[5,6,8,9]

The experimental investigations conducted included electric properties for PFA and PPX, such as dielectric constant and dissipation factor, measured in frequency range of 50 Hz to 100 kHz and at temperatures up to 200° C. The ac dielectric strength was obtained in the high temperature regime to 250° C. Since PBI allows higher maximum service temperature, its dielectric properties were obtained at temperatures up to 250° C, and the dielectric strength was measured at temperatures up to 300° C. The results obtained are presented in a comparative fashion. The investigation carried out in this paper is best oriented to give an experimental evaluation as well as a general assessment of the high voltage performance of Kapton, PFA, PPX, and PBI films at high temperatures.

EXPERIMENTAL PROCEDURE

25.0 μm thick Kapton, PFA, and PPX films, and 37.0 μm thick PBI film were used in this work. The dielectric constants and dissipation factors were measured at room temperature using GenRad 1689 Precision RLC Digibridge at eight different frequencies ranging from 50 Hz to 100 kHz. The surfaces of Kapton, PPX, and PBI specimens were coated with silver-loaded paint, while the surface of PFA film, due to its smooth and non-adhesive surface, was deposited with 100 nm thick aluminum electrodes to ensure good contact for all dielectric measurements. These properties were further characterized under high voltage high temperature conditions using a Tettex Instrument Precision Measuring System, Type 2822. The Tettex system is a high voltage high temperature bridge which is calibrated for utility power line frequency. The measurements were performed at temperatures up to 250° C with a voltage of 200 V, 60 Hz present.

The breakdown voltages of the films were obtained by employing a Hipotronics ac Dielectric Test Set, Model 7100-20A. A bath of silicone fluid 210 H, a high temperature dielectric oil supplied by Dow Corning, was used along with a temperature controller to obtain the desired test temperature within ±2° C. During each breakdown test, the specimen was sandwiched between the two cylindrical stainless steel electrodes, in accordance with ASTM-D149 standard, and the voltage was raised at a rate of 500 V/s until the sample failed. The values reported for breakdown are the mean-average of seven data points.

RESULTS AND DISCUSSION

Non-destructive dielectric characterization of the films that were carried out included the dielectric constant and dissipation factor both as a function of frequency and temperature, whereas the destructive characterization included the dielectric strength at 60 Hz. There was very little deviation in the data presented in Figures 1 to 4 with repeated measurements. Hence, for clarity, only a single data point at each frequency and temperature is reported. On the other hand, for breakdown measurement due to its statistical deviation, the mean-average of seven data points is reported.

The variation in dielectric constant of the specimens with increasing frequency at room temperature is shown in Figure 1. It can be seen that all materials do not exhibit any noticeable change in the dielectric constant with frequency. Figure 2 shows the effect of temperature on the dielectric constant of the four films. These measurements were carried out at 200 V, 60 Hz electrical stress. The results show that while the PFA film displays good stability with temperature, other films exhibit modest changes in their permittivity with an increase in temperature. That is, while the permittivity of PBI film seems to exhibit an increase initially and then remain constant, Kapton exhibits a slight decrease with increasing

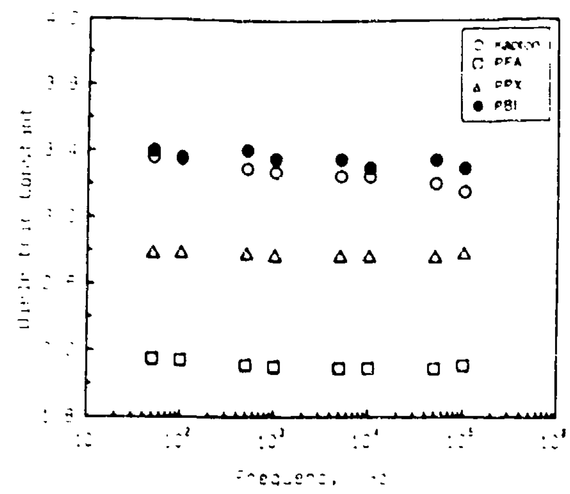

FIGURE:1 Dielectric Constant of Kapton, PFA, PPX, and PBI as a Function of Frequency at 22° C.

temperature. On the other hand, the permittivity of PPX remains unchanged up to 100° C and then undergoe slight increase as the temperature is further rai Polymers, in general, tend to soften at high temperature could undergo some degradation which may, in ' contribute to a change in permittivity.[10] The presenc electrical stress may have also contributed to the variatic this property.[11]

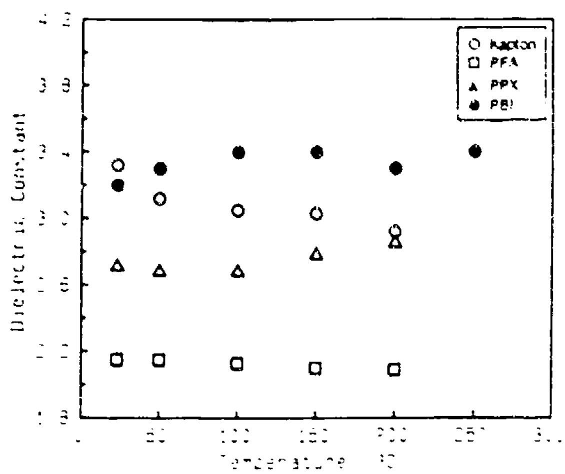

FIGURE:2 Dependence of Dielectric Constant of Kapton, PFA, PPX, and PBI on Temperature while Stressed at 200 V, 60 Hz.

The dissipation factor of the films as a functio frequency is plotted in Figure 3. PBI demonstrates highest dissipation factor of the four films, but is found t the most stable over the wide frequency range v compared with the other three materials. The dissip factor of PFA increases by about one order of magni while that of Kapton increase by half an order of magni with increasing frequency. Conversely, the property of decreases initially with an increasing frequency to 10 kH then starts to increase modestly with a further frequ increase.

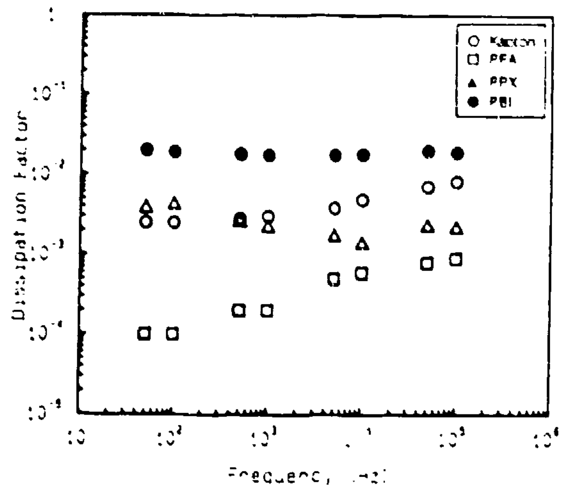

FIGURE:3 *Comparison of Dissipation Factor of Kapton, PFA, PPX, and PBI as a Function of Frequency at 22° C.*

The influence of temperature on the dissipation factor is shown in Figure 4. These measurements were performed while electrically stressed at 200 V, 60 Hz. PPX film in particular displays the largest increase in its dissipation factor with an increase in temperature, while PFA and PBI film exhibit a slight increase in their losses. On the other hand, the dissipation factor of Kapton does not change significantly with increasing temperature. PBI is the lossiest of the four materials, while PFA exhibits the lowest loss at high temperatures. The increase in the dissipation factor is generally attributed to an increase in free carrier concentration which often accelerates the breakdown phenomena.[12]

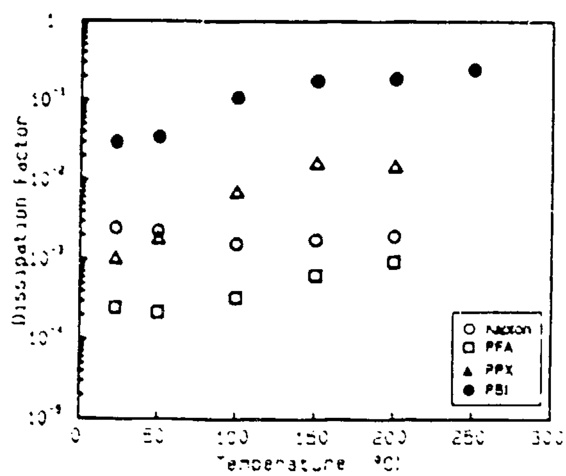

FIGURE:4 *Dissipation Factor of Kapton, PFA, PPX, and PBI as a Function of Temperature while Stressed at 200 V, 60 Hz.*

The dependence of dielectric strength of the materials on test temperature is shown in Figure 5. The breakdown sites were randomly distributed over the surface of the test specimen at all temperatures. The data obtained shows that even though Kapton has the highest dielectric strength at room temperature, it undergoes significant reduction in its breakdown voltage with an increase in temperature. PFA, like Kapton, also has a significant reduction in its dielectric strength with an increase in temperature. The decrease in dielectric strength of PFA and Kapton is about 40 % at 250° C as compared to their strength at room temperature. PPX and PBI, on the other hand, do not exhibit much change in their dielectric strength in the high temperature range. Most often, the decrease in dielectric strength can be attributed to the softening of the polymers when exposed to high temperatures.[13,14] In addition, a plausible explanation can be also given in simple terms to justify the occurrence of negative temperature dependence. When the applied voltage is raised, more energy is stored in the sample and more losses due to the dissipation factor, which is also known as dielectric loss, are generated and subsequently converted into heat. This heat raises the sample temperature which can not be dissipated outside due to the higher surrounding temperature. Consequently, at one instant, the so called critical temperature is obtained, causing the leakage current to increase rapidly which leads to the breakdown of the sample.[15]

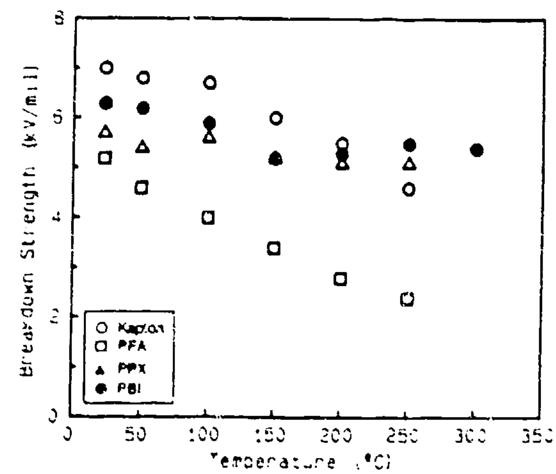

FIGURE.5 *Temperature Dependency of ac Dielectric Strength of Kapton (25.0 μm), PFA (25.0 μm), PPX (25.0 μm), and PBI (37.0 μm).*

CONCLUSION

The results obtained from the present studies on the four films (Kapton, PFA, PPX, and PBI) indicate few changes in their key properties at high temperatures and voltages. The dielectric constant of all materials remain unaffected for frequencies up to 100 kHz. Kapton and PBI display the highest dielectric constant of 3.4 while PFA shows the lowest dielectric constant of 2.1. In addition, the dielectric constant of both PPX and PBI films exhibits a modest positive temperature dependence when the temperature is raised. In comparing dissipation factors of the materials as a function of frequency, Kapton and PFA show an increasing trend while PPX exhibits a small decrease. On the other hand, the dissipation factor of PBI remains constant when the frequency is increased. However, its dissipation factor with respect to frequency is the highest of the four materials. Nevertheless, PFA, PPX and PBI display different increasing trends for dissipation factor with increasing temperature. That is, the dissipation factor of PPX increases by one order of magnitude, while for PFA and PBI, it goes up by approximately half an order of magnitude. However Kapton does not experience any significant change in its dissipation factor as the temperature is raised to 200° C.

Dielectric strength, which is one of the key properties for high voltage applications, shows strong negative temperature dependency particularly for Kapton and PFA films. This property for both PPX and PBI films, on the other hand, remains relatively stable with an increase in temperature up to 250° C. It is interesting to note that while Kapton displays higher dielectric strength at room temperature, PBI exhibits a higher dielectric strength in the high temperature regime (250°- 300° C) as compared to Kapton.

Good dielectric properties, especially a lower dissipation factor, could make PFA film more viable for low voltage high temperature applications. However, the stability and the dielectric strength of PPX and PBI at high temperatures could make them more useful for high voltage high temperature aerospace and space wiring insulation applications.

ACKNOWLEDGMENT

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REFERENCES

1. F. J. Campbell, "Reducing Wiring Fires in Naval Aircraft" *NRL Review*, Publication 123-2631, pp 117-118, July 1989.

2. J. Van Laak, "Kapton Wire Concerns for Aerospace Vehicles", Workshop on Wiring for Space Applications, NASA Lewis Research Center, Cleveland, Ohio, July 1991.

3. "Aircraft Wire Hazard Reported", Chicago Tribune, July 25, 1988.

4. C. Sawyer, "Space Station Freedom Secondary Power Wiring Requirements", Workshop on Wiring for Space Applications, NASA Lewis Research Center, Cleveland, Ohio, July 1991.

5. Du Pont, "Teflon PFA - Fluorocarbon Resins", Properties Bulletin E 80419, December 1986.

6. Nova Tran Corporation, "Abrasion Resistance of Parylene and other Conformal Circuit Board Coatings", Bulletin NTC # 400-0114-00, Nova Tran, Wisconsin, 1986.

7. J. F. Jones, J. C. Waldrop, and R. Fountain, "High Temperature Resistant Polybenzimidazole Composites for Missile Applications", *29th National SAMPE Symposium*, pp 777-783, April 1984.

8. E. J. Powers and G. A. Serad in *High Performance Polymers: Their Origin and Development* - Chapter on History and Development of Polybenzimidazoles, Eds. R. B. Seymour and G. S. Kirshenbaum, Elsevier Science Publishing Co., New York, 1986.

9. Du Pont, "Kapton - Summary of Properties" Bulletin # 72087, 1986.

10. P. J. Phillips in *Engineering Dielectrics Vol. IIA*, Chapter 2: Morphology and Molecular Structure of Polymers and their Dielectric Behavior, ASTM Publication, 1983.

11. R. Bartnikas in *Engineering Dielectrics Vol. IIA*, Chapter 1: Dissipation Factors in Solids, ASTM Publications, 1983.

12. J. L. Suthar and J. R. Laghari, "High Temperature Studies of Perfluoroalkoxy (PFA) Film", Proceedings of the Conference on Electrical Insulation and Dielectric Phenomena, Leesburg, Virginia, pp 495-502, 1989.

13. A. N. Hammoud and J. L. Suthar, "Characterization of Polybenzimidazole (PBI) Films at High Temperatures", Conference Record of the IEEE International Symposium on Electrical Insulation, Toronto, pp 449-451, June 1990.

14. J. L. Suthar, J. R. Laghari, and W. Khachen "Poly-P-Xylene Film for High Temperature High Voltage Dielectric Applications", Proceedings of Conference on Electrical Insulation and Dielectric Phenomena, Knoxville, Tennessee, pp 244-249, October 1991.

15. J. J. O'Dwyer, *The Theory of Electrical Conduction and Breakdown in Solid Dielectrics*, Oxford University Press, London, 1973.

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